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Soil-Structure Interaction Analysis in a Port Wharf Through Finite Element Methods Using the PLAXIS 2D Software

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Abstract. During the project lifespan, berthing structures are exposed to several types of stress. Mooring strains, weight of the structure and external loads from machinery and soil may generate stresses and displacements on the foundations. As they are structures that normally present a high level of complexity, the analysis of their behavior through numerical methods becomes an interesting tool. The use of these methods also allows to model the soil in a satisfactory way, since, as it is a heterogeneous medium, its properties are of difficult determination. The objective of this work is to use numerical methods as a way of analyzing the displacements and tensions imposed on the foundations of a port wharf. Standard penetration tests performed at the site were used to estimate the geotechnical parameters through correlations found in the literature. The numerical modeling was generated in the PLAXIS 2D AE. software, through a two dimensional plane-deformation analysis of the problem. Preliminary analysis identified the presence of these effects on the foundations of the wharf, thus showing the importance of their verification at the project stage. Through this work, it is expected to better understand the behavior of the soil-structure interaction present in this wharf, so that in future projects these effects can be taken into account.

Keywords: soil-structure interaction, deep foundations, finite element methods, PLAXIS 2D.

1 Introduction

When calculating any kind of structure, sometimes it is common among engineers to ignore the interaction between the superstructure, the soil and its foundations, considering them as rigid supports. This consideration does not correspond to the true behavior of the system, due to the fact that the tensions generated by the interaction between the structure and the soil can lead to a redistribution of these tensions.

The interaction between soil and structures is of great complexity and requires many calculations and parameters, making its study underestimated and generally used in expensive and large constructions. With the modernization of research and software that uses numerical methods in the engineering context, year after year the study of this interaction is being improved and is becoming an easier process.

Considering the great variability of the tensions and the aggressive ambient in which the berthing structures from the Rio Grande port area are placed, a deepened analysis is required to best understand its foundations behavior. In cases like this, with a complex situation, numerical methods prove to be a great ally of engineers as a way of predicting the behavior of structures.

In this article, numerical methods were used in order to simulate a wharf using a two dimensions model in the PLAXIS 2D software. Soil tests were used to help better understand the environment in which the pier foundation piles were inserted, so that the parameters used in the software were consistent with the reality.

2 Location and materials data

This study was carried out at a wharf located in the Honório Bicalho shipyard, located in Rio Grande city, south of Brazil. The analyzed structure is part of an expansion project of one of the companies operating on the site, and was designed to receive oil platforms to be assembled.

The wharf is divided in five sections with a total of 216 meters extension and its foundations consists of 373 vertically inserted concrete piles. In this work, the first connection platform piles are analyzed, so in the future the results can be used to model all sections.

2.1 Soil properties

The Rio Grande port region is constantly being studied not only by construction companies, but by researchers who try to better understand the soil characteristics. The soil parameters and behavior are difficult to analyze, especially due to the presence of intercalated layers of sand and thick layers of clay. In order to better design the foundations structure, a campaign of standard penetration tests (SPT) was carried out by the interested company at the site.

In this study the parameters used were obtained from the soil profile number 21 presented in Luzzardi [1], performed at the first connection platform location. The penetration resistance index (N_{spt}) obtained from the profile is presented in Fig. 1. This index was used through correlations to define the parameters used in the soil model.

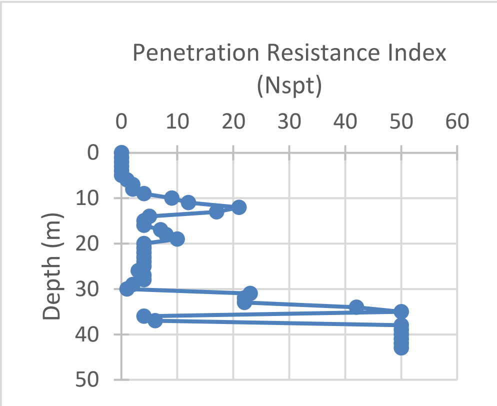

Figure 1. Soil profile according to the SPT test

Table 1 presents the defined layers found in the SPT, its characteristics and the defined parameters that were used in the model built in PLAXIS. The natural (γ), saturated (γ_{sat}) specific weight and the Young modulus (E) were obtained in Bowles [2] study, the friction angle (φ) in Cintra [3], the undrained resistance (S_u) with Stroud [4] formulations and Poisson coefficient (υ) was obtained in the research of Teixeira and Godoy [5].

Table 1. Soil parameters obtained with N_{spt} correlation

Layer	Soil Type	Classification	Average Nspt	γ (kN/m³)	γsat (kN/m³)	φ (º)	E (MPa)	Su (kN/m²)	Poisson
1	Sandy clay	Very soft	2	14.0	16.0		12.4	10.0	0.4
2	Sand	Med. compact	17	17.0	19.0	35.2	65.0		0.4
3	Sandy clay	Soft to medium	5	16.0	18.0		25.0	25.0	0.4
4	Clayey Sand	Med. compact	9	17.0	19.0	29.7	65.0		0.4
5	Sandy Clay	Soft to medium	4	16.5	18.5		45.0	20.0	0.4
6	Sand	Compact	32	17.4	19.4	42.7	67.6		0.4
7	Sandy Clay	Medium	5	17.5	19.5		57.5	25.0	0.4
8	Sand	Very compact	50	19.5	21.5	49.6	89.2		0.4

It is important to notice that the first sandy clay layer was completely removed for the construction of a hydraulic embankment. The soil properties of the embankment built in this area were the same as used in Almeida et. al [6], with a specific weight of 19 kN/m³, saturated specific weight of 21 kN/m³, Young modulus of 80 MPa and friction angle of 35º.

2.2 Pile and platform properties

The wharf foundation is made of hollow concrete piles with an external diameter of 80 cm and have 37.6 m long. The embedment depth is at 35 m and the piles are 2.6 m above sea level. The concrete has a compression resistance of 40 MPa, Poisson coefficient of 0.2 and specific weight of 25 kN/m³.

On the top of the piles there is a platform of 40 m length and 21.4 m width, with a 0.2 m thickness. The platform is made of the same concrete as the piles, so both have the same material properties.

2.3 Soil-structure interaction

In most of the cases, structures are designed considering the fact that the foundations will receive the tensions from the superstructure and stand still, but this may not represent their real behavior. Once the foundations transfer the tensions to the soil, it may suffer deformations that will generate new tensions on the foundations and consequently on the whole structure.

This process of forces and motion transference from the soil to the structure and back from the structure to the soil is known as soil-structure interaction. This is a complex process to study, especially due to the common soil heterogeneity and its non-linear response, and that’s the reason it’s not usually taken into account in small buildings.

There are two main analysis processes in the soil-structure interaction, the discrete and continuous models, and the main difference between them is the way the soil is modelled. This study was carried out using the continuous model, which enables a better modelling of the soil stratigraphy and could be used with the parameters obtained with the SPT soil profile.

3 Numeric methods and the software PLAXIS 2D

3.1 Finite elements method

Engineering problems are mostly solved through differential equations and by using numerical methods, it becomes easier to obtain these equations solutions. The finite element method (FEM) is one of those numerical methods, being used to solve situations by transforming a complex geometry into several minor parts.

Through the analysis of these small elements, it becomes easier to solve problems of great magnitude. The union of all these elements is called a finite element mesh, and usually the more refined the mesh is, the more accurate the results become, however demanding a higher processing capacity. By using FEM, it is possible to model not only the structures, but the soil non-linear behavior, multiple soil layers with accuracy and the complex geometry of the foundations.

3.2 PLAXIS 2D software

PLAXIS is mainly a software for analyzing geotechnical problems, ranging from analysis of percolation in soil dams to settlement and displacement in tunnels. It was developed in Delft Technical University in the Netherlands on 1993, and the version used in this study is the 2D Anniversary Edition. This software uses the FEM as a tool to solve problems involving structures and the soil in which they are built.

Presenting many tools as the different soil constitutive models, multiple mesh creation and quality analysis, dynamic loading, progressive stages analysis and graphics generator, this software was chosen by its capacity to best model the presented situation.

4 Situation modelling

A plane strain model was generated to simulate the wharf in PLAXIS 2D software. The model is 130 m length and 100 m depth, so the borders do not cause any additional stresses on the structure and the soil involving it.

4.1 Soil modelling

The soil was modelled using the 8 layers properties presented in the Tab. 1 and an additional layer representing the embankment, with the parameters mentioned in the item 2.1. Sand materials were inserted as drained (mostly affected by Young modulus and friction angle) and clay materials as undrained (mostly affected by undrained resistance).

All soil materials were generated with the predefined PLAXIS Mohr-Coulomb constitutive material model. This constitutive model considers the elasticity of the material until it begins to present a plastic behavior, defined by the Mohr-Coulomb rupture surface. Using this model, an average rigidity is estimated for each soil layer, which speeds up the calculation process. Formulations and advanced parameters regarding the Mohr-Coulomb model are presented by Brinkgreve and Broero [7], who refers this model as ideal for preliminary analyzes.

4.2 Structures and interfaces

Plate elements were used in this model to represent the piles and the wharf platform. These are structural elements used to represent thin elements in the soil, with three degrees of freedom. To use this element, it is necessary to inform the material axial and bending stiffness, specific weight, and its Poisson coefficient.

The concrete parameters and pile and platform dimensions mentioned in the item 2.2 were used in the model, however it is necessary to adapt some parameters as the model only have two dimensions. Out of plane columns of piles must be represented as "wall elements" in 2D. This transformation of the problem follows the same procedures of Ryltenius [8] study, as shown in Fig. 2.

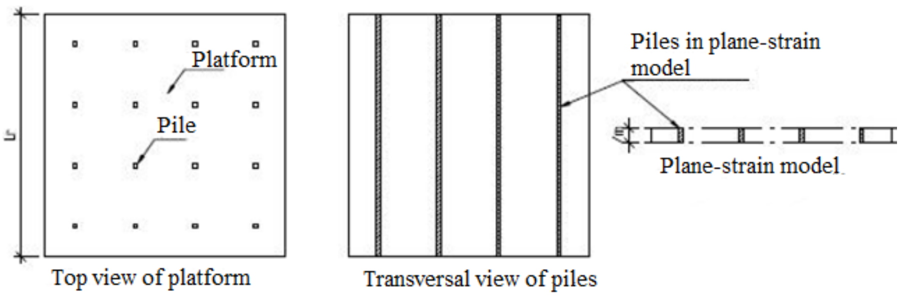

Figure 2. Plane-strain transformation scheme

As the "wall element" is defined meter by meter, normal and bending stiffness, and the weight of piles columns must be defined the same way. This procedure is done by multiplying the parameters of the 3D situation by the number of piles in each row ($n_{p\text{-}row\text{-}i}$) and then dividing it by the length of platform in the plane state (L_r) as shown in eq. (1):

$$EA_{plane-strain} = EA * \left(\frac{n_{p-row-i}}{L_r}\right). \quad (1)$$

After inserting the plane-strain structures and parameters, interface elements must be added to the piles. These elements are responsible for the soil-structure interaction in the model, representing the friction on pile walls and the adhesion of the soil to the interface. Brinkgreve and Broero [7] recommend extending the interfaces by at least 50 cm after the end of the elements.

The parameter responsible for this representation is the interface resistance reduction factor (R_{inter}). Ryltenius [8] suggest R_{inter} values of 0.7-0.9 for cohesive soils and 0.9 for non-cohesive soils. Zakia, et al.[9] proposed the use of a range from 0.8 to 0.9 for most of the situations.

The properties used in this plane-strain model are presented in Tab.2. For this model, the coefficient was defined as 0.85 for all types of soils. After adapting the coefficient to the plain-strain model, its value becomes 0.34. The adaptation is made by using eq. (2) as follow:

$$R_{inter,ps} = R_{inter} * \frac{n_{p-row-i} * A_s}{2L_r}. \tag{2}$$

Table 2. Pile properties used in the plane-strain (ps) model

Properties	Value	Unit
Normal stifness (EAps)	4450696.0	kN/m
Bending stifness (EIps)	178027.8	kN/m
Weight (wps)	3141593.0	kN/m/m

4.3 Mesh analysis

The initial model was generated with a medium refinement mesh made of 12396 nodes and 1467 elements of average size of 3.239 m. This refinement was used due to its good quality and relatively short processing time.

PLAXIS mesh analysis tool was used in order to verify the quality of the elements. In this analysis, a graphic color variation is used to demonstrate the quality of the elements, with green elements of good quality and red elements of poor quality. Figure 3(a) shows a mesh detail of the slope area, as well as the soil layers, piles, platform and loads. The good quality of the mesh analysis is shown in Fig. 3(b).

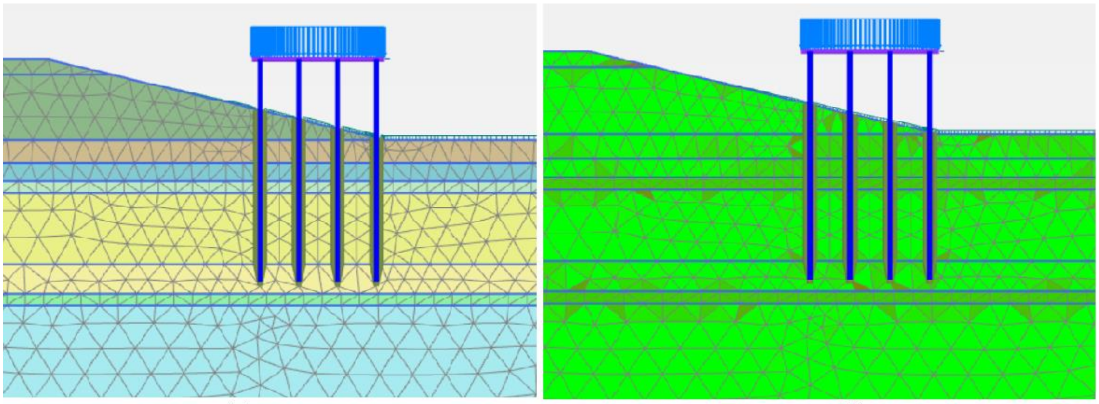
(a) (b)

Figure 3. Mesh details and quality analysis of model

5 Results

The first calculations were performed and after a preliminary analysis a problem with the slope stability becomes evident, especially in the second clay layer with 12 meters thick. The average values of undrained resistance (S_u) used through the correlation present in Stroud [4] evidenced to be underestimated for the specific case. The rupture surface is shown in Fig. 4(a).

It was decided then to use a previous study on the local soil to estimate new values for the S_u. Through the study of Dias et. al [10], S_u values of 49 kN/m² and 60.3 kN/m² were used to represent the resistance of the first and second clay layers respectively. After performing a new calculation step with the updated S_u values, extremely high displacements were found in the piles. Figure 4(b) presents the deformed mesh in which the pile close to the embankment crest suffered a settlement of 8.59 m.

The high settlements values show that the interaction between soil and piles used in the model do not represent the situation occurring on the wharf. At this settlement magnitude, the soil and pile may start to present a plastic behavior, thus having its results compromised.

Figure 5(a) shows the deformed mesh without scale of a new model generated with a hypothetical R_{inter} value of 0.6. The use of this interface coefficient presented better results for the stresses and displacements occurring on the wharf.

PLAXIS 2D has a plastic point analysis tool, which represents the points that have suffered plasticity through red dots in the model, as can be seen in Fig. 5(b). The plastic points concentrate at the piles, the embankment top and the interface between the last sand and clay soil.

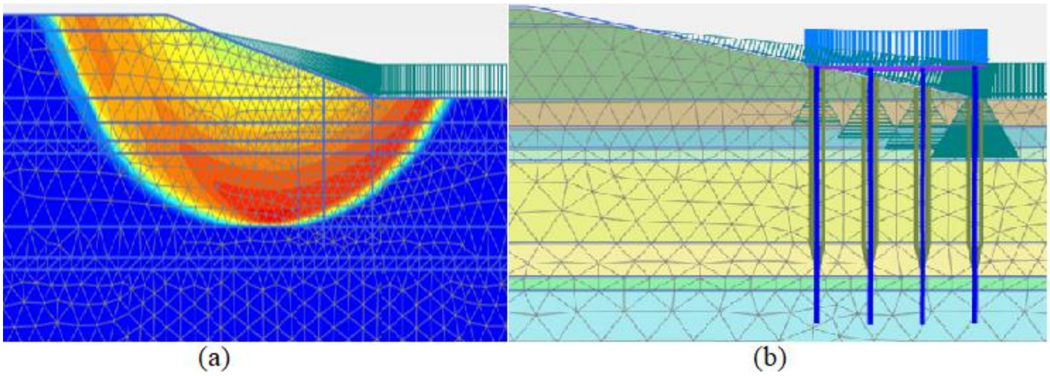

Figure 4. Rupture surface and interaction behavior of initial model

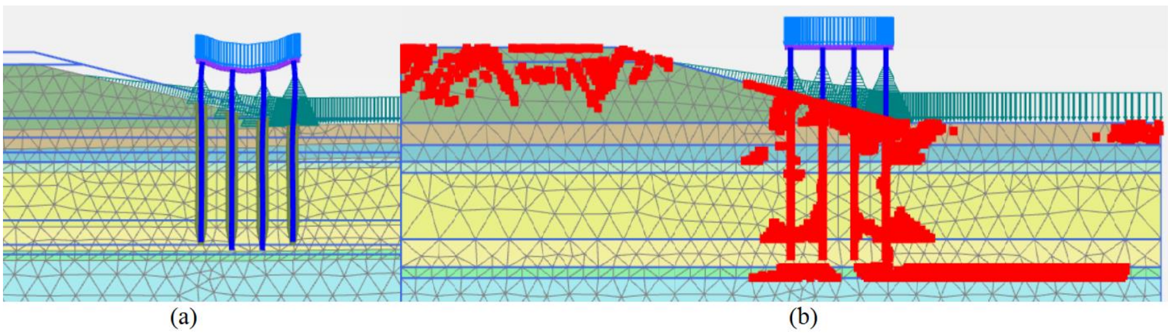

Figure 5. Deformed mesh and plastic points of new model

5.1 Displacements and forces on first pile

An analysis of the displacements and forces occurring on the pile next to the slope crest was carried out with the R_{inter} value of 0.6. This pile was chosen due to the high horizontal loads generated by the slope. Figure 6 shows respectively a representation of the axial forces, shear forces and bending moment, without scale, acting on the pile.

The graphs presented an axial force of 1606.0 kN/m acting on the selected pile. A negative shear force of 50.7 kN/m represents the pile reaction from the horizontal force of 160.0 kN/m applied on the pile by the slope. The bending moment presented a negative value of 1370.0 kNm/m while the positive value occurring on the first layer of soil is 163.6 kNm/m.

Using the new interaction coefficient, the maximum settlement was observed at the top of the pile with 0.403 m. It is evident that the pile is affected by the slope forces and, analyzing the horizontal effects occurred on it, a displacement of 0.107 m is observed. The use of a hypothetical value of interaction solved the great settlement on the piles, but they still presented high displacements.

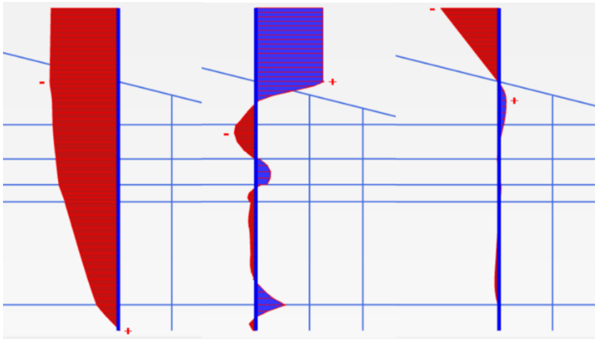

Figure 6. Forces representation on the first pile

6 Conclusions

First model analysis evidenced the underestimation of the undrained resistance from Stroud [4] proposal. The range of S_u from 4 to 6 times the N_{spt} value does not represent the local clayey soil, and should not be used to model clay properties on this region.

After a second stage of calculus using S_u values from local research, it was observed that the interaction factor used in the model presented significant settlements errors. By transforming the parameters of soil and piles from a 3D situation to a plane strain model using the procedures as seen on Ryltenius [7], the new R_{inter} value becomes too fragile, causing the piles to slip too much on the soil. It is suggested that in future researches a more realistic value for the interaction factor is used, then presenting a more accurate settlement of the piles.

It is concluded that the use of PLAXIS 2D as a tool for soil-structure interaction analysis should be supported by complementary studies of the local soil and materials. It is recommended to model the situation in a 3D software when studying piles, avoiding the parameters distortion.

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